

## MATERIALS



**S**tronger, lighter, and better insulating materials—the United States has received tremendous benefits from materials developments, particularly in the automobile industry. For example, new materials have allowed the introduction of lighter, yet stronger, automobile bodies and longer-lasting tires and batteries.

In a new era of miniaturization, researchers working at the atomic level have constructed a new class of advanced materials with properties far superior to those of conventional materials. These “nanophase” materials, which offer such characteristics as increased hardness, wear resistance, adhesion, and slipperiness, are useful in applications as diverse as microelectronics, automotive components, business machines, and even personal care products.

### Today's Market

Advanced materials offer benefits to diverse and growing markets, such as the automotive and nanotechnology industries. Stronger, lighter, and more affordable materials will help make the U.S. automotive industry more competitive. The chairmen of Chrysler, Ford, and General Motors each have stated that they expect 1997 U.S. vehicle sales to reach or exceed 15 million units.<sup>1</sup> Nanotechnology is here, and it is a multibillion-dollar worldwide industry with almost unlimited potential for growth. In particular, the nanophase materials market is expected to grow from \$300 million today to \$1.5 billion by 2001.<sup>2</sup>

### Tomorrow's Opportunity

BMDO research and development in materials has produced many innovations for ballistic missile defense systems. These innovations have been incorporated into new technologies that can help industry develop lighter automobile and satellite components, improve the thermal protection for aircraft flight data recorders, build higher-performance microelectronic devices, and produce smoother semiconductor polishes. The following section describes six such examples.

<sup>1</sup>American Automobile Manufacturers Association. 1996. Automotive Forecasts. World Wide Web at <http://www.aama.com/data/autofore.html>.

<sup>2</sup>British Parliament's Office of Science and Technology. World Wide Web at [http://www.nanothinc.com/NanoVentures/NanoMarkets\\_frames/nanomarketsframes.html](http://www.nanothinc.com/NanoVentures/NanoMarkets_frames/nanomarketsframes.html).

... a process that could help create automobile tires that provide better fuel efficiency, traction, and wear resistance.

APPLIED SCIENCES  
COLLABORATED WITH  
GENERAL MOTORS,  
GOODYEAR, AND OTHERS  
TO DEVELOP THEIR  
INNOVATIVE PROCESS.

## LOW-COST STRUCTURAL COMPOSITES MAY SOON HIT THE HIGHWAY

Composite materials are essential to the automotive industry's drive toward cars that are lighter, stronger, and more fuel efficient than their predecessors. Perhaps the most promising of these materials are carbon fiber composites. Stronger than steel, stiffer than titanium, and lighter than aluminum, carbon fibers could be added to a range of automobile components, giving them exceptional mechanical properties while significantly reducing their weight.

These enhanced properties come at a cost, however. Carbon fiber material costs much more than competing fibers and requires complex manufacturing processes. Such roadblocks have slammed the brakes on the use of carbon fiber composites in the automotive industry.

In a collaboration with General Motors Corporation, the Goodyear Tire & Rubber Company, and others, Applied Sciences, Inc. (Cedarville, OH), introduced a low-cost, high-volume process to produce vapor-grown carbon fibers (VGCFs). Developed with the help of BMDO SBIR contracts, VGCFs' range of properties—including high strength and light weight—make them an attractive fiber reinforcement in advanced composites. According to a survey conducted for Applied Sciences, VGCFs could cost less than \$5 per pound when produced at capacities greater than 10 million pounds per year. Competing fiber reinforcements cost \$100 per pound.

The National Institute of Standards and Technology's Advanced Technology Program recently awarded matching funds to the new development program, which also includes the Gas Research Institute, EMTEC, and GM Delphi Chassis Systems. The program will develop VGCF composites for automotive applications and address the technical hurdles associated with scaling the process to high-volume production.



■ The GM Ultralite, pictured above, epitomizes the objectives of Applied Sciences' work with GM and Goodyear. This 1,400-pound vehicle's fuel economy (100 miles per gallon) is achieved using carbon fiber composites combined with efficient powertrain and chassis systems.

One potential automotive application is in tires that provide better fuel efficiency, traction, and wear resistance. Economical production of VGCF composites could also help car makers reduce vehicle weight up to 132 pounds. Members of the venture also seek to develop VGCF anodes for lithium-ion batteries, which are attractive for all-electric vehicles because they can provide high specific power, high specific energy, and long cycle lifetimes.

Applied Sciences has also explored other applications for VGCFs; their high thermal and electrical conductivity make them attractive as battery electrodes, micro-electronic substrates, electromagnetic shielding, and static reduction composites. The company currently markets four products, and two more are nearly ready.

The BMDO SBIR program funded early development of Applied Science's VGCF technology in six projects, two of which received Phase II funding. These programs focused on developing VGCFs for electromagnetic railguns and for other structural, thermal, and electronic applications.

### ABOUT THE TECHNOLOGY

Introducing gas-phase catalysts into a heated hydrocarbon atmosphere produces VGCFs. The resulting fibers derive many of their attractive properties from the high degree of graphite crystalline phase that is produced. Individual fibers range in size from 100 microns ( $\mu\text{m}$ ) to several centimeters long, and from 0.2  $\mu\text{m}$  to 30  $\mu\text{m}$  in diameter. These size differences, along with the ability to combine fibers in several bulk shapes (from a cottonball-shaped tangle to a paper-like sheet), allow Applied Sciences to tailor the fibers' properties for many uses. The ability to coat the fibers with other materials provides further flexibility.

## MATERIAL STORES HEAT TO PROTECT FLIGHT RECORDERS

Recent plane crashes have highlighted the importance of flight recorders, devices contained in so-called “black boxes” that help officials determine the cause of airplane accidents. These boxes must withstand the destructive heat of a crash, protecting the recorders from serious damage. The Federal Aviation Administration (FAA) recently doubled the performance requirements of these black boxes, raising their required time of heat protection from 30 to 60 minutes.

Hayes & Associates (San Diego, CA) has developed new material for black boxes to protect flight recorders from thermal damage. Previous boxes manufactured and distributed by Smiths Industries used alloy-based heat sinks to absorb heat. Hayes’ new technology replaced these expensive, toxic heat sinks with smaller, cheaper, and less toxic material. In this application, the new heat sink improves cooling effects up to 400 percent and reduces manufacturing costs by 83 percent. After acquiring a license, Smiths Industries incorporated Hayes’ material into its Voice and Data Recorder™ product line, which consists of Cockpit Voice Recorders, Flight Data Recorders, and combined recorders for commercial and military aircraft.

This thermal storage technology, called Composite Fabric Endothermic Material, can easily be retrofitted in current black-box designs. This flexibility can reduce or eliminate the airline industry’s reengineering costs to address black-box requirements. Currently, Smiths Industries is working with Hayes to enhance the material’s thermal performance to meet the FAA’s 60-minute requirement. Hayes originally developed the material for BMDO’s Laser Shield project for temperature control in aerospace vehicles.

Hayes & Associates’ multilayer material also can be tailored to do the opposite—first store and then slowly release heat over a prolonged period. For example, in a licensing deal with Pepsico, Hayes has developed a material for Pizza Hut to heat carts that sell pizza away from the stores, delivering the food at 140°F to 180°F, even after the food has sat in the cart for hours. Pizza Hut uses the material in thermal plates heated with the pizza in the oven; carts bearing the thermal plates warm the pizza until delivery to factories, sporting events, and cafeterias.

Rigid or flexible, Hayes’ material molds into cups, plates, and panels. It could even be applied to clothing; when people go out in the snow, they could first zap their gloves in the microwave, so the gloves—and the wearers’ hands—will stay warm.

### ABOUT THE TECHNOLOGY

The multilayer materials consist of an inner region of thermally active material sandwiched between protective outer layers of plastic or metal. The inner section may contain a polymer that undergoes a thermochemical reaction or phase change to absorb and release heat at a critical temperature. The key aspects of Hayes’ patented technology include (1) active materials that retain large amounts of heat and (2) the ability to tailor the material to temperature and time-at-temperature requirements.

When heated, the temperature of the composite material increases to the critical point; the material holds this temperature while continuing to absorb heat until saturation. At that point, the temperature may still increase further. On cooling, the reverse trend occurs, with the temperature falling rapidly to the critical point and remaining there for an extended period until the internal thermochemical processes are exhausted.

. . . a thermal storage material that protects aircraft flight recorders from destructive heat in plane crashes.

HAYES’ NEW MATERIAL IS FINDING HOT MARKETS IN FLIGHT RECORDER PROTECTION AND FOOD DELIVERY OPERATIONS.



■ Smiths Industries’ Voice and Data Recorder™ products, pictured above, are more resilient to heat using Hayes’ thermal storage material.

... a carbon composite that will provide better heat control for high-power electronic equipment on satellites.

ROI IS FOCUSING ON SPACE APPLICATIONS FOR THE NEAR TERM, BUT PLANS TO PURSUE OTHER MARKETS.

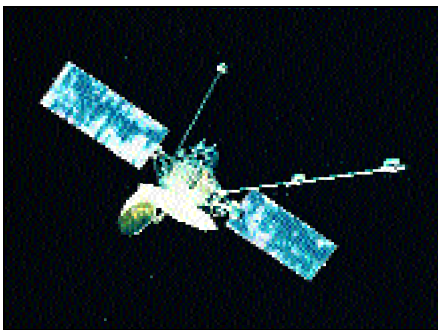
## HEAT-CONDUCTING COMPOSITE PROTECTS SATELLITE COMPONENTS

Engineers designing satellites and high-performance aircraft face the conflict of requiring more while needing less. They require more in that they must continuously increase the performance of their vehicles, using high-powered electronics to meet military and commercial missions. At the same time, they require less in that they must find ways to reduce or maintain the vehicle weight, despite increased capabilities. They also require less in that new technology must be relatively low cost to meet mission budgets.

Research Opportunities, Inc. (ROI; Torrance, CA), developed a process that tailors the thermal properties of specially prepared carbon composite structures to meet the stringent packaging requirements for high-power electronic modules. The processed materials have a much higher thermal efficiency than conventional metal components at lower cost than advanced high-thermal conductivity materials, such as diamond. ROI also designs thermal management interfaces that match the material characteristics of attached electronic devices. This matching ability prevents failures of solder joints and adhesive bond lines caused by differences in thermal expansion between the device and its enclosure.

BMDO-funded research at ROI led to lay-up, machining, and cure techniques for the composite structures. The materials have twice the thermal conductivity of copper (850 watts per meter Kelvin) at one-fifth the density. Their light weight and high strength make them especially useful in thermal management applications. Some examples of applications include thermal doublers, radiators, and equipment shelves for satellites. In aircraft, the materials can be used for electrical component cooling and thermal dissipation at hot spots. They also can serve as heat spreaders for gallium arsenide-based microelectronics.

ROI offers full-scale thermal measurement services and maintains an electronic database of over 10,000 measured properties of high thermal conductivity composites. The company plans to pursue other markets as the price of the material decreases, while focusing on space applications for the near term.



■ ROI's carbon composite structures are ideal for satellite applications where light weight and high strength are important.

### ABOUT THE TECHNOLOGY

To fabricate the carbon composite structures, ROI uses a self-reinforced graphite (SRG) called ThermalGraph<sup>®</sup>, produced by Amoco Performance Products Division. ROI machines the SRG "brick" into a wafer design, cross-plying it in alternating right angles and then sandwiching it with metal such as aluminum. Laminate thickness ranges from about two micrometers up to one centimeter. The thermal expansion properties of the heat source and sink materials determine the relative thicknesses of the SRG and the aluminum.

Tailoring SRG to thermal management applications involves innovative processing and machining techniques developed with BMDO funding. Special resin impregnation and curing techniques produce dense SRG with a graphite volume fraction of 90 percent. Carefully selected adhesive materials for laminating metals to the impregnated SRG allow minimal stress in the SRG while preventing adhesive shear failure, or separation along the grain, over a broad range of operating temperatures.

## PURE AND LOOSE, NANO-SIZED PARTICLES MAKE BETTER MATERIALS

As the feature sizes of electronics shrink below the wavelengths of visible light, semiconductor manufacturers will require nanopowder-based optical polishes for smoothing the surfaces of silicon wafers. To be effective, powder particles must have uniform sizes and must resist the tendency to clump together, or agglomerate. Larger-than-average particles or particle clusters can create defects on the surfaces of wafers, which can cost up to \$50,000 to replace.

Under BMDO SBIR funding, Structured Materials Industries, Inc. (SMI; Piscataway, NJ), developed a nanopowder production process that may produce the next generation of ultrasmooth polishing compounds. The company can produce nonagglomerated nanoparticles with narrow size distributions for a variety of materials, including metals, oxides, and nonoxides.

SMI formed a new division called Nanopowder Enterprises, Inc. (NEI; Piscataway, NJ), to manufacture and sell the nanoparticles to industry. NEI has already received orders from the semiconductor manufacturing industry for sample quantities of Nanomyte™ nanopowder abrasives. In addition, the company is making a titanium dioxide sun-blocking agent. Titanium dioxide particles in sun-blocking lotions tend to clump together, weakening their ability to deflect the sun's harmful rays. NEI's nonagglomerated nanoparticles eliminate this clumping effect, improving the lotion's sun-blocking properties.

The company also sells a low-cost tool for producing nanoparticles. The Nanomyte One™ produces a wide variety of nanopowders in the 3- to 50-nanometer range. It features several modules that enable different processes to fabricate the nanoparticles.

SMI and Rutgers University originally developed the nanopowder production process to make silicon and germanium light-emitting nanocrystals for BMDO displays. The company continued the original research and recently demonstrated that silicon emits white light (full-color, including ultraviolet, visible, and infrared light) when electrically stimulated. More recently, SMI developed a line of transparent conductive oxides and electroluminescent and cathodoluminescent oxides.

With these initial successes in hand, SMI has already planned the first product for its films, a green electroluminescent flat-panel display. The NanoChrome Display could be an economical alternative to liquid crystal displays.

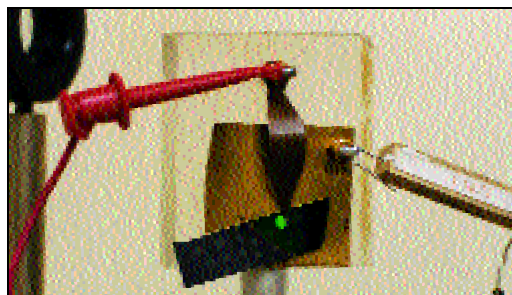
### ABOUT THE TECHNOLOGY

SMI developed a dry, chemical vapor condensation process that produces nonagglomerated nanoparticles. In the process, reactant chemicals ride an inert carrier gas and pass through a reaction chamber. This chamber can be an evaporation chamber, a hot wall chamber, a combustion flame, or a plasma source, any of which will force condensation. During condensation, by-products dissipate as vapors. The remaining products are dry, nonagglomerated nanoparticles.

The nonagglomerated nanoparticles have a narrow size distribution, because the residence time for the reactant chemicals equals that of the carrier gas for all gas streams as they move through the chamber. Selecting an oxidizing, reducing, carbonizing, or nitridizing atmosphere controls the particular compound chemistry, as required. Multiple chemical reactant sources form multicomponent, multiphase particles. This process controllably produces nanopowders from 3 to 50 nanometers in size.

. . . a process that can produce nanopowders to make smoother semiconductor polishes and stronger sun-blocking lotions.

TO MANUFACTURE AND SELL NANOPARTICLES TO INDUSTRY, SMI FORMED A NEW DIVISION CALLED NANOPOWDER ENTERPRISES, INC.



■ BMDO-funded research is helping SMI develop the first product for its film, a green electroluminescent flat-panel display

... silicon transistors that promise impressive performance advantages over today's micro-electronic devices.

NANODYNAMICS HAS  
TEAMED WITH INFINITE  
TECHNOLOGIES, INC.,  
TO PRODUCE WORKING  
PROTOTYPES.

## SILICON MAKES A QUANTUM LEAP IN MICROELECTRONICS

Conventional silicon transistors have enjoyed spectacular success over the past three decades, but size limitations of the technology threaten future progress. If transistors shrink much below 0.1 microns, the barriers that control switching functions will no longer operate properly. Also, as the devices shrink, the amount of heat within a chip builds up, requiring costly thermal management solutions.

To address these problems, NanoDynamics, Inc. (New York, NY), is building silicon-based superlattice devices called quantum transistors. These devices will use semiconductor heterostructures with thicknesses approaching those of an atom to overcome the heat build up common in integrated circuits. The razor-thin layers will allow the current to flow according to the rules of quantum tunneling without electron scattering, which causes heat. BMDO is funding this research through an SBIR Phase II contract for smaller, faster, and cooler electronics.

The most innovative aspect of this project is the use of silicon. Combining the low cost of silicon-processing technology and the high performance of column III-V semiconductor superlattices, this technology is an attractive replacement for many microelectronic devices. Because the technology also permits optical transitions in silicon, it ideally suits all light-using applications of solid-state devices, including lamps, light-emitting diodes, flat-panel displays, optoelectronics circuits, and photon detectors.



■ Pictured above is Nanodynamics' newly built fabrication chamber, which can control the fabrication process accurately down to fractions of an atomic layer.

NanoDynamics built the working diodes based on its BMDO-funded technology. Its next step connects the diodes in a working transistor. Toward this end, the company teamed with Infinite Technologies, Inc., to produce linear transistor prototypes. NanoDynamics and Infinite Technologies are jointly creating a new company, Dallas Linear Devices, with the goal of gaining 1 to 2 percent of the semiconductor market within five years. NanoDynamics currently estimates this market at \$150 billion, possibly reaching \$300 billion in the next six years.

### ABOUT THE TECHNOLOGY

To deposit the superlattice, NanoDynamics alternates layers of silicon and partial layers of silicon oxide. The structural differences between the two layer types produce localized strain regions in the semiconducting medium. These regions form quantum wells for the electrons in the medium. Applying voltages to the electrons in the wells enables such electronic functions as transistor amplification, diode current control, and switching. Theoretically, the quantum wells can be packed in high densities, allowing smaller transistors.

## RIGID PLASTIC FLEXES ITS MUSCLES FOR STRUCTURAL APPLICATIONS

Cheap and durable, plastic has an amazing track record in replacing a wide range of metals. However, it falls short in applications requiring a combination of high strength and stiffness. For example, under heavy loads plastic without enough stiffness bends. To compensate for this problem, material processors often add glass and carbon fibers—an expensive, additional manufacturing step—to stiffen plastic.

With BMDO SBIR funding, Maxdem, Inc. (San Dimas, CA), developed a new family of rigid-rod polymers that are more than four times stiffer than conventional plastic materials. Called Poly-X™ Self-Reinforced Polymers (SRPs), these inexpensive, durable materials could replace structural materials—including certain types of aluminum and stainless steel—particularly in automotive, aerospace, and defense applications. They also could substitute for expensive fiber-reinforced composites.

For example, the company is working to develop a Poly-X SRP resin to replace the fiberglass sheet molding compound (SMC) used in automotive body panels. Unfilled Poly-X plastics could decrease vehicle weight and facilitate recycling, impossible with current SMCs because of their high fiberglass content.

In another application, Poly-X SRPs could work in laminate form for printed circuit boards and electronics connectors. These harder, more abrasion-resistant polymers could also make highly scratch-resistant windows for automobiles, airplanes, machinery, and windows. The polymers might also be used for brakes, clutches, and other parts.

Funding from the BMDO SBIR program is helping Maxdem to scale up the Poly-X SRP production process, to bring Poly-X SRPs to market. Currently, Maxdem's small-scale production facility regularly produces 22-pound batches of the polymers. It supplies these batches to companies that may develop new applications. According to Maxdem's projections, Poly-X SRPs will cost \$10 to \$12 per pound when production achieves 5 million pounds per year.

### ABOUT THE TECHNOLOGY

Poly-X SRPs are rigid-rod polymers with exceptional strength and stiffness. For example, the elastic modulus, or stiffness, of Poly-X SRPs ranges from 1 to 2.5 million pounds per square inch (psi). In contrast, the modulus of conventional engineering resins ranges between 300,000 to 600,000 psi. Unlike liquid crystal polymers, whose strength lies in one direction, Maxdem's rigid-rod materials are equally strong in all directions.

Poly-X SRPs are unique thermoplastic resins based on amorphous rigid-rod polymers. These polymers possess carefully chosen pendant side chains (the flexible component) to impart tractability to the rigid-rod polyparaphenylene backbone. Maxdem's proprietary production process ensures the isometric integrity of the rigid-rod structure. Therefore, homopolymers (the repetition of a similar molecular chain) and copolymers (the repetition of two or more molecular chains) can readily be prepared.

... rigid-rod polymers, over four times stiffer than conventional plastic materials, that could compete with some types of metals.

MAXDEM SUPPLIES  
BATCHES OF POLY-X™  
SRPs TO COMPANIES  
THAT MAY DEVELOP  
NEW APPLICATIONS.



■ Maxdem's Poly-X™ SRPs can be fashioned into molded parts and composites, as shown above. They also can be made as resins, pellets, films, and solutions.